The Importance of Neutrino Opacities for the Accretion Luminosity in Spherically Symmetric Supernova Models

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General Relativistic Boltzmann Neutrino Transport

Spherically symmetric simulations of stellar core collapse and postbounce evolution do not lead to explosions if they are based on "standard" [1, 10] nuclear and weak interaction microphysics. This widely anticipated statement achieved a completely new level of justification with the technically complete and self-consistent treatment of neutrino transport in the highly dynamical evolution after core collapse and bounce [16, 14] in general relativity [2, 11]. Multidimensional models for core collapse supernovae, which allow non stratified hydrodynamics at the cost of reliable neutrino transport, present the neglect of convection as a plausible cause for the failure to reproduce supernova explosions in spherical symmetry (e.g. see Ref. [6] and references therein). In our spherically symmetric models, neutrino absorption adds only weakly to the entropy of the shock-dissociated material after shock stagnation because of high infall velocities. Nevertheless, spherically symmetric models provide a field for further studies: The realistic neutron star structure and the accurate evolution of angle- and energy-resolved neutrino distribution functions enable the investigation of the influence of nuclear and weak interaction physics on the models. Complete implicit radiation hydrodynamics also provides insight into many tightly coupled processes with strong feedback in the evolution of a core collapse supernova.

In the following, we compare the postbounce evolution of five different initial stellar progenitors, simulated with general relativistic three-flavor Boltzmann neutrino transport. The chosen progenitors have masses of 13 $M_\odot$ and 20 $M_\odot$ [15]; and 15 $M_\odot$, 25 $M_\odot$, and 40 $M_\odot$ [17]. We present in Fig. 1 the shock position for these different models as a function of time, as solid lines. We find similar trajectories for all progenitors, with a shock radius maximum around 150 km. We also plot the shock position in terms of enclosed mass in Fig. 2b: Before the existence of a shock during core collapse, we plot the deleptonization-dependent position of the sonic point where the shock will form after bounce. In a later stage, the gradient of the shock trajectory reflects the accretion rate given by the radial density profile of the progenitor star. Also shown are the electron neutrino luminosities and rms energies in Fig. 2a. Among the chosen progenitors, which represent the full progenitor mass range of expected type II events, the most striking feature is the clear separation into a quantitatively similar evolution up to the electron neutrino burst and a distinctively different one afterwards.

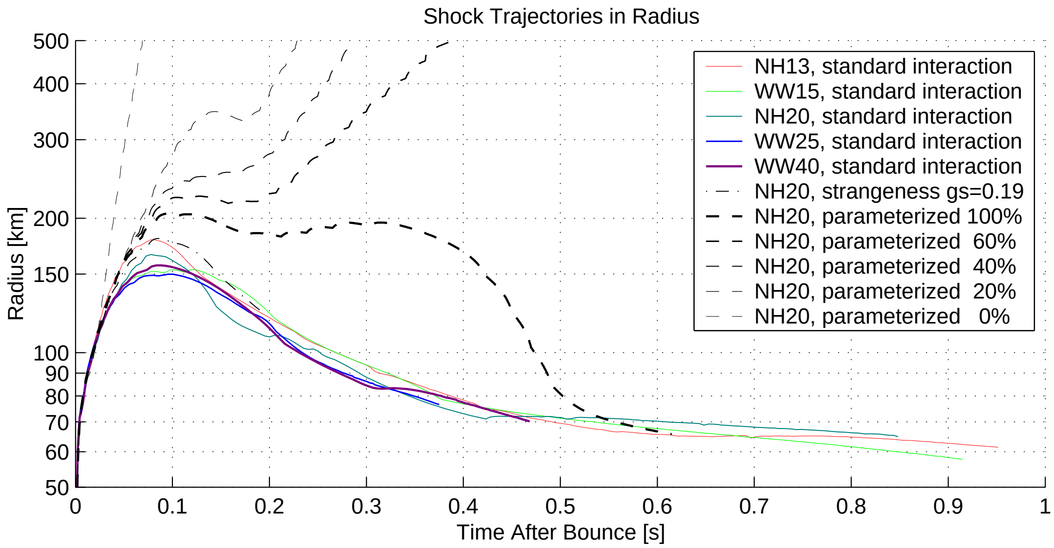

Figure 1: Shown in solid lines are the shock trajectories with standard input physics. Dash-dotted is the shock trajectory of the 20 solar mass progenitor with nucleon strangeness content included. The experimental dashed trajectories (based on transport with lowest angular resolution) show explosions as a function of parametrized isoenergetic scattering on free nucleons.

Feedback in the Deleptonization during Core Collapse

When the inner core of the progenitors reach the Chandrasekhar mass, they have comparable density and temperature profiles. The electron fraction determines the location of the sonic point at the surface of the inner core, which is causally connected by electron pressure (Fig. 2b). During collapse, the electron fraction decreases by electron capture on nuclei and protons until trapped neutrinos block further deleptonization. A regulation mechanism establishes similar electron fractions in all models [1, 12]: The small abundance of free protons, Y_p, is given by the Lattimer-Swesty equation of state as a function of the electron fraction, Y_e. The sensitivity $d\ln(Y_p)/dY_e \sim 30$ is large enough that a small deviation, $\Delta Y_e = 0.01$, from a "normal" Y_e-evolution changes the proton abundance, and therewith the number of electron captures on free protons, by a third. This negative feedback drives the electron fraction back to the "norm"-evolution whenever electron captures on free protons dominate. In our simulations, capture on heavy nuclei is suppressed as soon as the $N = 40$ shell is closed [1]. Thus, the described self-regulation sets in at this point, leading to very small differences in the evolution of the different progenitors up to shock breakout. The extent to which this regulation survives extension of electron capture rates to heavier nuclei, when these rates are computed with improved nuclear shell models, remains to be investigated.

Accretion Luminosities and Neutrino Opacities

The accretion luminosity, which dominates over the core diffusion luminosity soon after shock stall, is produced by the compression of infalling material at the surface of the PNS. The available energy can roughly be estimated by the rate of infalling material, multiplied by the gravitational potential at the neutrino sphere. The result is an energy deposition rate that qualitatively relates the modulation in the observable neutrino luminosities to accretion

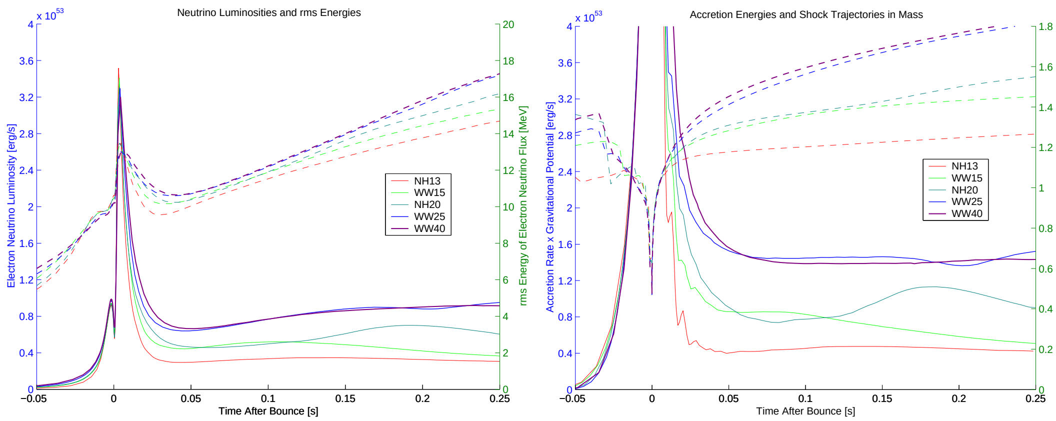

Figure 2: The left hand side shows the electron neutrino luminosities (solid) and rms energies (dashed). On the right hand side are the accretion energy rate (solid) and the sonic point/mass trajectories in enclosed mass (dashed).

rates (Fig. 2ab), i.e. to variations in the initial density profiles of the progenitor stars. A relation of this kind might be linked to analytical supernova models that present conditions for shock revival as a function of independent luminosities and accretion rates [3, 7]. The main influence of nuclear input physics to the evolution of the shock position resides in how the high density equation of state determines the size of the PNS on the one hand, and how the neutrino opacities at moderate densities ($\sim 10^{13}$ g/cm^3) affect the energy loss rate by neutrino emission on the other:

Indeed, reduced isoenergetic scattering opacities at moderate densities have led to explosions in spherical symmetry and suggested a search for an exploration of the physical limits. However, a physically justifiable opacity reduction by taking into account the strangeness content of nucleons (see e.g. [9]) did not produce explosions, even if it had a positive effect in exploratory runs (Fig. 1). A detailed discussion of the degrees of freedom in the nuclear input in this regime has been given in Ref. [5]. A parameter study with decreased opacities beyond physical limits (Fig. 1) shows an interesting side effect: In exploding models, we find electron fractions close to 0.5 in the inner layers of ejecta as soon as the electron degeneracy is lifted in the neutrino heated, expanding material. The electron fraction changes during mass ejection will be considered in upcoming nucleosynthesis calculations of supernova yields [4].

With standard opacities at moderate densities, the microphysics above nuclear densities affects the postbounce evolution more by influencing the size and stability of the PNS than by influencing the diffusive neutrino flux. A more compact PNS puts the accretion/heating cycle deeper into the gravitational potential, resulting in higher infall velocities and luminosities [2, 11]. An explosion-enhancing effect from the deeper gravitational potential can only be obtained if the PNS contraction is fast enough to produce very high luminosities before the heating region has adjusted to the smaller PNS radius, or if the outer layers are kept at a distance by a yet unidentified mechanism. PNS convection may provide a more visible consequence of changes in the high density physics [8, 13]. However, a definitive conclusion regarding the effect of convection below and around the neutrino sphere awaits a more refined equation of state and the inclusion of detailed multidimensional neutrino transport.

Acknowledgements

M.L. is supported by the National Science Foundation under contract AST-9877130. O.E.B.M. is supported by funds from the DoE HENP Scientific Discovery through Advanced Computing Program. A.M. is supported at the Oak Ridge National Laboratory, managed by UT-Battelle, LLC, for the U.S. Department of Energy under contract DE-AC05-00OR22725. W.R.H. is supported by NASA under contract NAG5-8405 and by funds from the Joint Institute for Heavy Ion Research and a DoE HENP PECASE Award. F.-K.T. is supported in part by the Swiss National Science Foundation under contract 20-61822.00. K. L. is supported in part by the Danish Research Council. We thank the Institute for Nuclear Theory at the University of Washington for its hospitality and the Department of Energy for partial support. Our simulations were carried out on the National Energy Research Supercomputer Center Cray SV-1.

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